Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

A99.9 F764Un

Research Note RM-510

July 1991

USDA Forest Service
Rocky Mountain Forest and
Range Experiment Station

A Method for Constructing Site Index Curves from Height-Age Measurements Applied to Douglas-Fir in the Southwest[1]

Carleton B. Edminster,[2] Robert L. Mathiasen,[3] and William K. Olsen[2]

A methodology for constructing site index curves from height-age measurements using an estimated guide curve and 95% confidence intervals for individual predictions is developed based on data for Douglas-fir in Arizona, New Mexico, and southwestern Colorado. These curves are compatible with site tree data collected in forest inventories.

Keywords: *Pseudotsuga menziesii*, site index, site quality

THIS RESEARCH NOTE SUPERSEDES RESEARCH NOTE RM-326.

The height of dominant trees of a given age relates more closely to the productive capacity of a given forest site than does any other single measure (Spurr and Barnes 1980). For most commercial forest species, height-age relationships are the basis for constructing site index curves, which continue to be the most commonly used index of forest site quality. Previously available site index curves for Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) in the Southwest were developed from height-age measurements from stands dominated by Douglas-fir in a limited geographic range in northern and central New Mexico (Edminster and Jump 1976). Those curves were anamorphic and were not tested across the range of stand conditions in the Southwest.

Two basic methods are available for constructing site index curves. The first involves stem analysis or recurrent measurement of permanent sample trees, selected to exclude those subjected to height growth inhibiting injuries, diseases, insects, or suppression (Curtis 1964, Stage 1963). Recent studies indicate a preference for stem analysis because a height growth pattern is obtained from each sample tree, the analysis procedures allow for polymorphic curve form, and the height of the tree is measured at the index age. Most studies using stem analysis techniques have been fairly limited in geographic range because of the intensive measurements required on each sample tree. Reliable use of the curves requires that trees measured for comparison with site index curves have sustained no height growth inhibiting damage or suppression. Such damage can often be detected through intensive stem analysis, but may not be detectable during standard forest inventories.

The second method involves constructing a guide curve from one-time measurements from a large sample of trees (Chapman and Meyer 1949, Osborne and Schumacher 1935). While this approach is efficient in sampling large geographic areas, it does have certain weaknesses. The site index for a given sample tree can only be inferred if it is assumed that all sites are sampled equally across the range of ages—an assumption that may be unrealistic if the study is not properly designed. Also, while methods are available to construct polymorphic curves using the basic guide curve, measurements over time from a single tree are not available to test curve form. Because trees sampled for site index curve construction using the guide curve method and

[1]*Data collection for this study was conducted under a research contract between the USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, and the School of Forestry, Northern Arizona University, Flagstaff.*

[2]*Mensurationist and Forester, respectively, Rocky Mountain Forest and Range Experiment Station. Headquarters is in Fort Collins, in cooperation with Colorado State University.*

[3]*Pathologist, Department of Lands, Coeur d'Alene, Idaho.*

subsequent forest inventories are from similar populations of trees as they exist in the forest, bias in sampling trees with undetectable height growth inhibiting injuries may be reduced (Brickell 1968). This second method may have added advantages when we are sampling trees in uneven-aged, mixed species stands where it may not be possible to detect past suppression in the current dominant portion of the stand.

Despite its limitations, the guide curve method was implemented in this study because it was the most efficient procedure for sampling a large geographic area. Sampling was designed to meet basic assumptions of the method, and to include observations from uneven-aged stands to test whether curve form portrays actual height development for a given stand.

Data Collection

Sample plots were located to adequately cover the range of commercial site qualities on national forests across the Southwest, where Douglas-fir is a major component of commercial forest stands (table 1). Plots were located within areas of apparent uniform site quality. Field sampling included uneven-aged stands to allow testing of the resulting site index curves against height development patterns for a range of tree ages at a single location. Selection of sample trees was further limited by the constraints that the distribution of sample trees by site index should be representative within each 10-year age class, and equal representation of a particular site quality should occur in all age classes.

At each plot, trees selected for measurement were in the dominant crown class in even-aged stands or were dominants or potential future dominants in younger age classes in uneven-aged stands. Trees selected for sampling were at least 10 years old at breast height and not more than 210 years old. Heights were measured to the nearest foot. The sample trees were of good form, without excessive sweep or crook, sound for ring counts to the pith from an increment core extracted at breast height (4.5 feet above ground on the uphill side of the tree), and with no visible evidence of crown damage, such as broken or forked tops, disease, or infestation by insects. For a tree to be included in the sample, the increment core must have shown a normal pattern of ring widths from cambium to pith, indicating no obvious evidence of past injuries or extended suppression.

Table 1.—Number of plots and Douglas-fir trees sampled for site index curve development, by national forest.

National forest	Plots	Trees
Arizona		
Apache-Sitgreaves	74	344
Coconino	11	32
Kaibab	20	88
New Mexico		
Carson	44	116
Gila	9	44
Lincoln	25	105
Santa Fe	59	172
Colorado		
San Juan	53	224
Total	295	1125

Height-age data points from the current study were compared graphically with data points from the previous study of Douglas-fir site index in northern New Mexico (Edminster and Jump 1976) before data from the two studies were pooled. As expected, data points from the earlier northern New Mexico study were in the lower portion of the height measurements across the range of ages when compared to the region-wide data from the current study. The data from the earlier study did have a better representation of points for lower values of height at ages over 80 years, however. A total of only 49 trees from that study had ages greater than 80 years and height values less than the range represented by the current study; these were included in the analysis to improve representation of poorer sites at older ages. Other observations from the New Mexico study that overlapped data from the current study were not included to avoid biasing results toward lower site qualities from a limited geographic area. A total of 1,174 tree measurements were available for subsequent analysis.

Analysis

Unweighted nonlinear regression was used to compare the fit of the height-age measurements to various mathematical models:

$$HT = b_1 (1 - b_2 \exp(b_3 AGE))^{b_4} + 4.5 \quad [1]$$

(Richards 1959)

$$HT = b_1 + b_2 \exp(b_3 AGE) + 4.5 \quad [2]$$

(Grosenbaugh 1965)

$$HT = AGE^2 / (b_1 + b_2 AGE + b_3 AGE^2) + 4.5 \quad [3]$$

(Prodan 1968)

$$HT = \exp(b_1 + b_2 AGE^{-1} + b_3 AGE^{-2} + b_4 AGE^{-3} + b_5 AGE^{-4}) + 4.5 \quad [4]$$

(Farrar 1981)

$$HT = b_1 / (1 + b_2 \exp(b_3 AGE^{b_4})) + 4.5 \quad [5]$$

(Monserud 1984)

where

HT = total tree height (feet)
AGE = age at breast height (years)
exp = exponential function
b_i = parameters to be estimated

When we used coefficients of determination computed as the proportion of the corrected sums of squares of HT accounted for by the regression, the Richards model (equation [1]) resulted in a 2.4% to 8.1% improvement in fit relative to the other models. In addition, a plot of the curve on the height-age data showed it was satisfactory over the entire age range. The plot demonstrated that the variance of the height measurements increased

with increasing age, however. An iterative weighted nonlinear regression procedure was then used to develop the final guide curve with the form of the Richards model. The weighting function used in the nonlinear regressions was the reciprocal of regression estimated variance of height based on age at each iteration. Iterations were continued until the estimates of the parameters of the model showed negligible change from the previous iteration. The final guide curve equation was

$$HG = 109.559\ (1-0.9759\ \exp\ (-0.0144\ AGE))^{1.2893} + 4.5 \qquad [6]$$

where

HG = total tree height (feet) on the guide curve.

The weighted coefficient of determination and standard error of estimate were 0.865 and 0.99 feet, respectively. The corresponding unweighted coefficient of determination and standard error of estimate were 0.781 and 13.1 feet. A plot of the data, guide curve, bounds for approximate 95% confidence intervals for the mean, and bounds for approximate 95% confidence intervals for an individual prediction (SAS 1988) are shown in figure 1.

As the next step in developing the family of site index curves, we examined the assumption that height-age curves for different site indexes are proportional to the shape of the guide curve, using the method employing the coefficient of variation of height described by Chapman and Meyer (1949). The assumption of proportional shape was not supported as there was a definite curvilinear downward trend in a plot of the coefficient of variation of height with increasing age. Nonlinear regression was used to fit a negative power function of age to the coefficient of variation of height values. This function of age was then used in computing the adjustment factors for the site index curves, and a family of tentative site index curves was plotted. Comparison of the family of curves to the dispersion in the data showed that the curves in the upper and lower ranges of site index were considerably beyond the range of data points for ages up to about 120 years. This tentative family of curves was rejected, and an alternative method was sought for developing the site index curves.

As figure 1 shows, the bounds for approximate 95% confidence intervals for individual predictions are appropriate for describing variability of the data around the guide curve as they include both variability associated with the model and variability of the data (Graybill 1976). At the reference age of 100 years, the lower 95% bound, guide curve, and upper 95% bound are equivalent to site indexes of 56.2, 82.5, and 108.8 feet, respectively. An alternative method for computing height-age values for a family of site index curves involved using the guide curve and the relative distance from the guide curve to the bounds of the confidence intervals for individual prediction. For each site index at the reference age, a proportion (P) was computed by dividing the vertical distance from the site index value to the guide curve by the distance from the guide curve to the upper or lower bound of the 95% confidence intervals for individual prediction. This proportion was then multiplied by the distance between the guide curve and the upper or

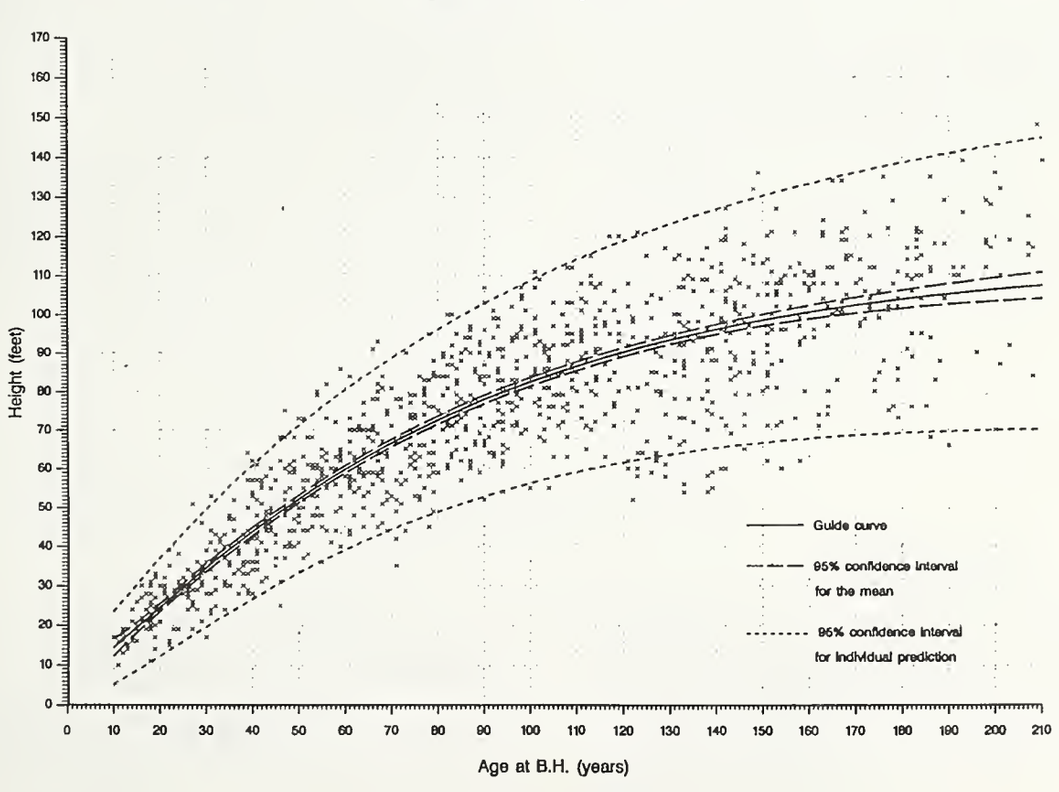
Douglas–fir site index guide curve
Height (feet)
Age at B.H. (years)
Guide curve
95% confidence interval for the mean
95% confidence interval for individual prediction

Figure 1.—Guide curve and bounds for 95% confidence intervals for the mean and individual prediction in relation to the distribution of height-age data for all trees.

lower bounds for the confidence intervals to locate the site index curves over the range of age. This method produced the series of site index curves shown in figure 2. The resulting curves are polymorphic in shape and portray the dispersion in the height-age data points. It should be noted that the curves for site index 40 and 120 are extrapolations beyond the range of available height values. This procedure did result in the site index 40 and 50 curves showing a slight decrease in height for age values greater than 178 and 201, respectively. The curves for site indexes 40 and 50 in figure 2 were set to horizontal above these ages. Estimated values of height for the site index curves are given in table 2.

To further check the shape of the site index curves, we selected from the data set 50 plots from uneven-aged stands that represented the range of site indexes and with tree heights measured over a wide range of tree ages. At ages greater than 50 years, trees from 42 of the plots were within half of a 10-foot site class interval of the computed average site index for the plot, and the maximum error was less than 1.5 times a class interval. This verification supports the shape of the curves in figure 2. As expected, there was considerably more dispersion in estimated site index values for ages less than 50 years.

Next in the analysis sequence, we attempted to develop a single model that adequately described the family of site index curves in figure 2. A 5-parameter extension of the Richards growth curve (Ek 1971) was fit to the values in table 2, but performance of the model was poor, especially at low and high values of age for low and high values of site index. We abandoned this approach in favor of providing a methodology parallel to development of the site index curves by proportional distances from the guide curve and the bounds for 95% confidence intervals for individual prediction. When we used height-age values for the lower bound shown in figure 1, the following equation resulted from nonlinear regression:

$$HL = 72.513\ (1-0.8770\ \exp(-0.0201\ AGE))^{2.0166} \quad [7]$$

where

HL = estimated height (feet) of the lower bound of the 95% confidence interval for individual prediction.

The resulting coefficient of determination was nearly 1.0 and standard error of estimate was 0.2 foot. Use of this equation in computing site index is described in the following section.

Field Application

Trees measured for site index determination should be selected from within a stand area of apparent uniform site quality. The results from the above verification suggest that trees selected for site index determination be at least 50 years old. At least 6 dominant trees in a stand should be measured (Johnson and Carmean 1953), and more trees are suggested if it is necessary to sample trees from more than one age class. Given the opportunity for damage to have affected height growth in older trees, we recommend that trees generally not be over 150 years old. Trees selected should be in the dominant crown

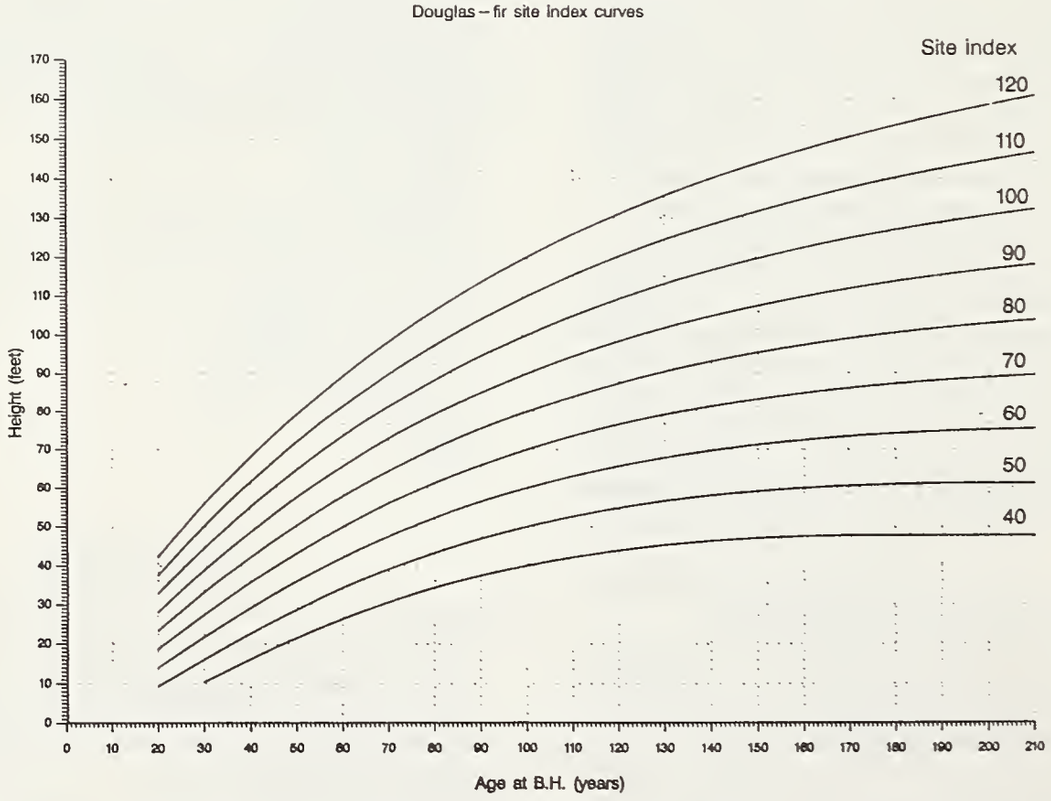

Figure 2.—Site index curves for Douglas-fir in Arizona, New Mexico, and southwestern Colorado. Reference age 100 years, breast height.

Table 2.—Estimated total height (feet) of Douglas-fir trees in the dominant portion of the stand.

Breast height age (yrs.)	Site index class								
	40	50	60	70	80	90	100	110	120
20	4.6	9.3	14.0	18.7	23.4	28.1	32.8	37.5	42.2
30	10.3	16.0	21.7	27.4	33.1	38.7	44.4	50.1	55.8
40	16.1	22.6	29.1	35.6	42.1	48.6	55.1	61.6	68.1
50	21.5	28.7	35.9	43.2	50.4	57.6	64.8	72.0	79.2
60	26.4	34.2	42.1	49.9	57.8	65.7	73.5	81.4	89.3
70	30.6	39.1	47.5	56.0	64.4	72.9	81.3	89.8	98.2
80	34.3	43.3	52.3	61.3	70.3	79.3	88.3	97.3	106.3
90	37.4	46.9	56.4	65.9	75.5	85.0	94.5	104.0	113.5
100	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0
110	42.1	52.6	63.1	73.5	84.0	94.4	104.9	115.3	125.8
120	43.9	54.8	65.6	76.5	87.4	98.3	109.2	120.1	131.0
130	45.2	56.5	67.8	79.1	90.5	101.8	113.1	124.4	135.7
140	46.2	57.9	69.7	81.4	93.1	104.8	116.5	128.2	139.9
150	46.9	59.0	71.2	83.3	95.4	107.5	119.6	131.7	143.8
160	47.4	59.9	72.4	84.9	97.3	109.8	122.3	134.8	147.3
170	47.6	60.5	73.3	86.2	99.0	111.9	124.7	137.6	150.4
180	47.7	60.9	74.1	87.3	100.5	113.7	126.9	140.1	150.3
190	47.7	61.1	74.7	88.2	101.8	115.4	128.9	142.5	156.0
200	47.7	61.2	75.1	89.0	102.9	116.8	130.7	144.6	158.5
210	47.7	61.2	75.4	89.6	103.8	118.1	132.3	146.5	160.7

class. If it is necessary to select trees in other than the dominant portion of the stand, they should be dominants in younger even-aged groups. Increment cores from selected trees should show no evidence of extended suppression or injury. Trees with a period of tightly spaced rings longer than normally associated with drought—for example, between periods of normal growth—should be avoided. Trees should show no evidence of disease, crown damage, sweep, or crook. In stands where it is not possible to select suitable trees not infected by dwarf mistletoe (*Arceuthobium douglasii* Engelm.), sampling should be limited to trees with a dwarf mistletoe rating (Hawksworth 1977) of 2 or less. Because it may be necessary to sample more than one age class in a stand, it is recommended that a site index value be computed for each sample tree, and then averaged for the stand.

Site index may be computed from height-age measurements by two-way interpolation in table 2 or by applying the following 4-step calculation using a programmable calculator. The user is cautioned that this method may result in some rounding and estimation error. This error will usually be less than 0.5 foot, which is less than the normal acceptable error in height measurement of standing trees, however. In these calculations, only the lower bound for the confidence interval is considered, as the bounds are symmetric about the guide curve.

1. For a measured tree age (AGE), compute the height of the guide curve (HG) using equation [6].

2. For the same AGE, compute the height of the bound of the lower 95% confidence interval for individual prediction (HL) using equation [7].

3. Compute the proportion (P) described in the "Analysis" section. P = (HG–HT) / (HG–HL), where HT is the measured tree total height.

4. Compute estimated site index (SI). SI = 82.488 –26.279 P.

Computer Application

The listing of DFSITE, a FORTRAN subroutine to compute site index based on the above procedure, appears below. Input parameters to the subroutine are total tree height in feet (HT) and breast height age in years (AGE) for a sampled tree. The estimated site index is returned as the output parameter SI.

```
      SUBROUTINE DFSITE (HT,AGE,SI)
C SUBROUTINE TO COMPUTE SITE INDEX FOR
C DOUGLAS-FIR IN THE SOUTHWEST.
C INPUT HT (TREE HEIGHT) AND AGE (AGE AT B.H.).
C OUTPUTS SI (SITE INDEX).
      TEM = AGE
      IF(TEM .GT. 210.0) TEM = 210.0
      HG = 109.559129*(1.0-0.975884*EXP(-0.014377*
     + TEM))**1.289266 + 4.5
      HL = 72.512644*(1.0-0.876961*EXP(-0.020066*
     + TEM))**2.016632
      P = (HG-HT)/(HG-HL)
      SI = 82.488-26.279*P
      RETURN
      END
```

Literature Cited

Brickell, James F. 1968. A method for constructing site index curves from measurements of tree age and height - Its application to inland Douglas-fir. Res. Pap. INT-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 23 p.

Chapman, Herman H.; Meyer, Walter H. 1949. Forest mensuration. New York, NY: McGraw-Hill Book Company. 522 p.

Curtis, Robert O. 1964. A stem-analysis approach to site-index curves. Forest Science. 10: 241–256.

Edminster, Carleton B.; Jump, Lewis H. 1976. Site index curves for Douglas-fir in New Mexico. Res. Note RM-326. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 3 p.

Ek, A. R. 1971. A formula for white spruce site index curves. Forestry Research Note No. 161. Madison, WI: University of Wisconsin. 2 p.

Farrar, Robert M., Jr. 1981. A site-index function for naturally regenerated longleaf pine in the East Gulf area. Southern Journal of Applied Forestry. 5: 150–153.

Graybill, Franklin A. 1976. Theory and application of the linear model. North Scituate, MA: Duxbury Press. 704 p.

Grosenbaugh, L. R. 1965. Generalization and reparameterization of some sigmoid and other non-linear functions. Biometrics. 21: 708–714.

Hawksworth, Frank G. 1977. The 6-class dwarf mistletoe rating system. Gen. Tech. Rep. RM-48. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 7 p.

Johnson, Floyd A.; Carmean, Willard H. 1953. Sampling error in estimation of site index. Journal of Forestry. 51: 26–27.

Monserud, Robert A. 1984. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. Forest Science. 30: 943–965.

Osborne, J. G.; Schumacher, F. X. 1935. The construction of normal-yield and stand tables for even-aged timber stands. Journal of Agricultural Research. 51: 547–564.

Prodan, Michail. 1968. Forest biometrics. Oxford, UK: Pergamon Press. 447 p. [Translated by Sabine H. Gardner.]

Richards, F. J. 1959. A flexible growth function for empirical use. Journal of Experimental Botany. 10: 290–300.

SAS Institute Inc. 1988. SAS/STAT user's guide, release 6.03 ed. Cary, NC: SAS Institute Inc. 1028 p.

Spurr, S. H.; Barnes, B. V. 1980. Forest ecology. 3rd ed. New York, NY: John Wiley and Sons, Inc. 687 p.

Stage, Albert R. 1963. A mathematical approach to polymorphic site index curves for grand fir. Forest Science. 9: 167–180.